

HIGH EFFICIENCY SOLAR CELL PROCESSING

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INTRODUCTION

At the time of writing, cells made by several groups are approaching 19% efficiency (AM1) (already achieved by the UNSW group). To help focus the forum objectives, we have chosen to discuss some more general aspects of the processing required for such cells, rather than presenting detailed cell results.

Most processing used for high efficiency cells is derived from space-cell or concentrator cell technology, and recent advances have been obtained from improved techniques rather than from better understanding of the limiting mechanisms.

Theory and modeling are fairly well developed, and adequate to guide further asymptotic increases in performance of "near-conventional" cells. There are several competitive cell designs with promise of higher performance (>20%) but for these designs further improvements are required.

The main trend recently has been the increased number of groups which can combine the available technology to fabricate high efficiency cells, and later we will discuss this trend in relation to the goals of the forum.

HIGH TECHNOLOGY PROCESSING

The available cell processing technology which has been exploited can be listed as follows:

- Choice and use of high quality silicon (mostly highly doped, mostly float-zone refined).
- Processing to preserve the high quality of the silicon.
- Formation of polished or textured front surface with low damage, accompanied later by the formation of a well designed (and carefully deposited) AR coating.
- Formation of shallow, lightly doped, good quality PN junction (usually by diffusion, in some cases by ion-implantation).
- Use of contacts with low contact resistance, perhaps with tunnel oxide layers to reduce recombination.
- Use of grid patterns with low shading (3-4%) and reduced series resistance (few %), giving fill factors above 0.80.
- Use of front surface passivation.
- In some cases, use of fields, reflectors or passivation at the back surface.

In addition, when required, space cell groups have demonstrated the fabrication of thousands of thin (50-100um) cells with high efficiency.

Tables 1 and 2 show the intrinsic and extrinsic properties required for high efficiency cells, along with the process steps which mainly determine these properties. We have also indicated the cell parameters most affected.

TABLE 1

INTRINSIC CELL PROPERTIES AND PROCESS STEPS WHICH
INFLUENCE THESE PROPERTIES

<u>INTRINSIC PROPERTY</u>	<u>PROCESS STEPS</u>	<u>AFFECT</u>
HIGH BULK DIFFUSION LENGTH	STARTING SILICON, CLEANING, PROCESSING	Jsc
GOOD JUNCTION QUALITY	SURFACE PREPARATION, CLEAN DIFFUSION	Voc (CFF)
LOW BULK LEAKAGE CURRENT	JUNCTION, PURE SILICON, DOPING OF SILICON.	Voc
LOW SURFACE RECOMBINATION	SURFACE PASSIVATION (BSF, FSF, OXIDES, ETC.) MIN. METAL (AREA, PASSIVATION)	Voc (Jsc)
SHALLOW JUNCTION	DIFFUSION CONTROL	Jsc

TABLE 2

EXTRINSIC CELL PROPERTIES AND INFLUENCING PROCESS STEPS

<u>EXTRINSIC PROPERTY</u>	<u>PROCESS STEPS</u>	<u>AFFECT</u>
LOW REFLECTANCE	AR COATING, (TEXTURED)	Jsc (Voc)
LOW SHADING	GRID DESIGN	Jsc
LOW RESISTANCE LOSS	GRID DESIGN, LOW CONTACT RESISTANCE	CFF

INTERACTIONS

SILICON QUALITY/PROCESSING

JUNCTION QUALITY/SHALLOW JUNC./PASSIVATION/GRIDDING

SURFACE PREPARATION/AR/PASSIVATION

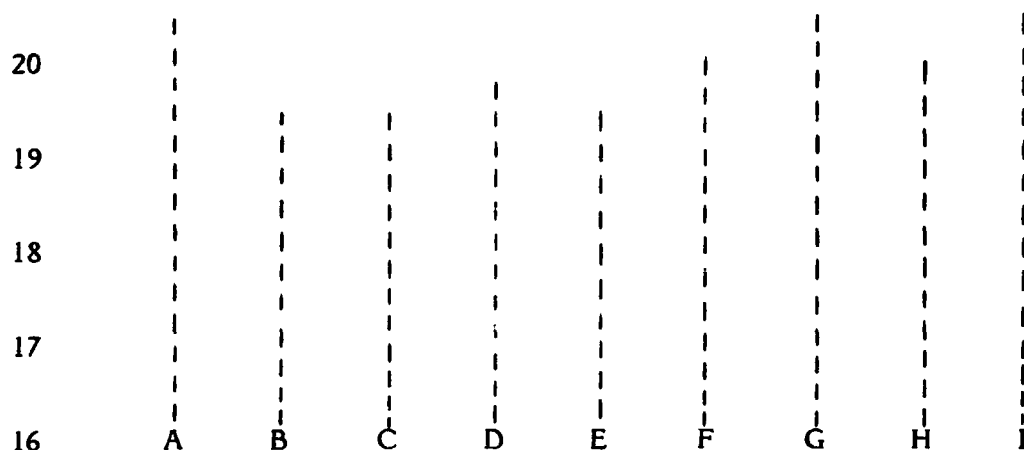
If can be seen that there is considerable interaction of the process steps. This emphasizes the fact that to equal (or exceed) the best state-of-the-art cell performance, most of the processes listed must be acquired and combined successfully. In fact the main requirement is to minimize the unwanted interactions as far as possible. Often the key requirements eg. texturing and passivation, are in conflict.

In some cases, the effect of a different (hopefully improved) process can only be evaluated by including it in a cell fabrication sequence with most of the other necessary steps. Experience shows that to achieve the best cell performance, all the process steps must be applied well.

In other cases, involving severe conflict of process steps, relief is sought by moving to alternate structures. For example, use of mostly back surface structures, can ease the shading and passivation requirements, but may lead to the need for higher carrier diffusion lengths, and for effective back surface passivation, as well as requiring a more complex (interdigitated) contact design.

In a few cases, the conflicts are resolved by using more complex steps eg. the use of "dot" contacts to reduce metal Si contact area, and to reduce the need for contact passivation. Figure 1 shows pictorially the high technology processes which have been combined to give ~19% and it can be seen that a fairly good level of optimization is needed for almost all the steps.

FIGURE 1
EFFICIENCY ACHIEVABLE WHEN VARIOUS PROCESSES OPTIMIZED



EFF (AM1.5)
(%)

PROCESS FUNCTION

- LEGEND:**
- A GOOD QUALITY SILICON
 - B SURFACE PREPARATION
 - C QUALITY JUNCTION
 - D SHALLOW, LIGHTLY DOPED SURF. LAYER.
 - E REFLECTANCE LOW.
 - F LOW SERIES RESISTANCE
 - G REDUCED SURFACE RECOMBINATION.
 - H LOW SHADING AREA.
 - I CONTACT PASSIVATION

If some of the steps (e.g. G or I) are omitted, 17-18% is still achievable (this is the level often seen on production runs of space or concentrator cells).

To exceed 18%, most of the processes shown must be well controlled and combined. To reach 19-20%, it is important to make improvements in steps A, G and I.

Silicon Quality

Most of the present high efficiency designs, and most of the projections for further increase to ~20%, involve the use of very high quality silicon.

Almost all high efficiency cells have used float zone refined silicon, often with multiple zone passes. Such high quality silicon in the high doping ranges required, is not readily available (high efficiency solar cells represent a very limited market), and the quality is not easily specified or guaranteed. In fact, there is danger that the highest efficiencies claimed world-wide could all have been obtained using very few (perhaps one or two) ingots. This is of academic interest to show the feasibility of the combined processes to meet the design goals, but additional action is required if these cell designs are to be useful for meeting long term flat plate efficiency goals (array efficiencies in excess of 15%, at a price of \$90 per square meter, and with 20-30 years projected lifetime).

We have had much experience with Czochralski-grown silicon, but limited experience with highly doped Cz-Si. Generally for equivalent doping concentrations, cell efficiencies are lower by 1-2% in conversion efficiency (5-10% lower in power), when Cz-Si replaced Fz-Si. However, lightly doped Cz-Si has shown very good quality, and very little work has been done to check if the problems at high doping levels are derived from the doping pellets used, or from crucible interactions. Although the latter would appear to be the cause when comparing to the zone-passing improvements, it is hard to explain why lightly doped Cz ingots are so good. Micro-tron technology has made significant improvements in the quality of surface devices, by use of internal gettering. It appears that more work should be done to identify the causes for reduced performance of highly doped Cz-Si. For production purposes Cz-Si has proved capable of high throughput and high quality, and although not yet satisfactorily inexpensive, it still is competitive with most other types of silicon.

DISCUSSION

We have indicated above that:

- a) Continued optimization of cell technology (mostly already used at low "production" levels) can provide cells ~20% efficient; also most of the same technology can be deployed to test new cell designs.
- b) The feasibility of cells which can meet the efficiency requirements for future flat plate arrays, has been demonstrated.
- c) At present, in order to demonstrate small improvements, it is necessary for each group involved to master most of the processes required to make a cell.
- d) Most designs rely on use of very special quality silicon.

However, there are some important areas which require assessment, especially for this forum:

- i) More work is required, to widen the choice of silicon, which has the chance of meeting the long term goals.
- ii) Although it is necessary at present to show successful combination of all the process steps, in the long run it is inefficient to expect various cell development groups to acquire all these processes. In some cases, the time spent in such acquisition detracts from effort in areas where their real technical strengths can be used, whether it is in cell modeling, or in development of new processes.

The only solution to this appears to be the formation of "teams", wherein the basic processing skills are used to complement some of those groups.

Consideration of this option, leads to the realization that there are several different motives which drive cell development, including basic interest in theory and practice, commercial interest in the flat-plate array goals, the need to obtain financial gain or prestige for establishments or self, or even patriotism. These motives must be reconciled to make best use of all available talents.

- iii) Now that the cell technical requirements have reached a competitive efficiency plateau (19-20% cells should meet 15% array goals) it is not too early to begin assessment of the cost and production limitations, and also to demonstrate adequate environmental stability. Here again, as in (i) a different set of skills may be needed, and it is important that some of the groups developing cells should be attuned to interaction with production groups.
- iv) A minor consideration is offered - that perhaps a cell design should be selected which can be used in both flat plate and concentrator arrays (with slight known modifications for the latter) as the best compromise for short term production evaluation.
- v) In parallel with (iii), work should continue to extend the demonstrated feasibility (towards 23-25%) either by routes which do not demand utilization of many precise technology process steps, and which overcome some physical limitations (eg. high doping effects), or perhaps by effective team efforts.

Some of the areas discussed above can be explored by decisions reached after the forum, by suitable direction from JPL or other agencies.

SUMMARY

Using near-conventional cell structures, present cell process technologies, when suitably combined can give cell efficiency ~19%, and with slight improvements, mostly in Si quality, 20% seems feasible.

The successful designs to-date are derived from space and concentrator cell technologies which have demonstrated medium scale production levels (100KW flat-plate output per year), although without meeting the flat-plate array cost goals.

We feel that already manufacturing assessment should be made for cells operating in the 19-20% plateau.

Some theoretical designs offer the possibility of exceeding 20%, and should be pursued without constraints of costs, etc.

One non-technical purpose of the forum maybe to combine the various motivations involved, to provide an effective program; one area of promise is the deliberate formation of balanced teams which include a wide range of skills (and motives).

DISCUSSION
(ILES)

CISZEK: Peter, I'm intrigued by these older space cells that were worked out at AMO and a lot of people say they would have done real well under terrestrial conditions. Isn't it possible to dig some of those out from the old Spectrolab or OCLI cells that are textured?

ILES: Yes, they are still being made. The strange thing is that textured cells have only been made for a limited run and a different reason. The textured cells run 10°C to 15°C hotter in space, and most people in the terrestrial areas don't understand that, that we can get a higher efficiency on the block but we don't get a higher efficiency when we interface with a real system. Space cells are a little more sophisticated, and the customer puts his specifications in there very early on and he knows very well what he is going to gain. I'm sure you are right. Matter of fact, I think Daud wanted some decent cells, back-surface fields so that he and Fred Lindholm and some other people could find out whether there was a voltage drop at the back surface. They came and got some Class 2 mechanical reject cells -- we don't make that many back-surface fields. He took them back and phoned us the next day and said do you know these are 17 something percent, and we said yes, you never asked us what, you just wanted some Class 2 cells.

CISZEK: It would be interesting to hear more of the results on some of those space cells and see how they really stack up terrestrially.

ILES: I think the bottom line is they look very like these other cells; these are mainly 10 ohm-centimeter with a good back-surface field. It's hard to compare the 0.1, 0.2 ohm-centimeter concentrator-type cells. They are not very different in diffusion, gridding -- all those things are very similarly done. We can get you some of them if you want to analyze them.

RALPH: Here I'd like to pin you down, I guess, as you have heard, we all have put in bells and whistles and that type of thing to make our cells and we all can agree that we could make like 17% with the bells and whistles we put in daily. What would you do different to get the 19% jump? In other words, there has to be something additional. Is it just resistivity change, or is it plus the passivation, or is it the material that's limiting it? What would you do different, what additional bells and whistles would you add?

ILES: At the moment, the material is the driving factor. To look very carefully, you want to get 19% with high yield -- we are not talking about the best of the week or the best of the month. I think you have to divide the maximum diffusion length on the material and a reasonably high doping level. I don't think at the moment -- the trade-off to having lighter doping and a back surface field is not quite competitive, but very close when you get to that level. It's not easy in production but quite feasible to make shaded areas at one sun less than 3%. I think that would be no big deal. It would be a little tricky for a while but not unfeasible. The coatings and everything else are fairly straightforward. That's why I get so frustrated -- now we are talking about

production levels in a solar cell that is largely still hand production, but these processes are being automated for very large scales and, in different areas like the coatings, as you know, automated by different industries. The diffusion and the slicing and the polishing, all that stuff is well taken care of. So I think that the answer is that it's just a matter of putting them together. It depends on the material. I think it's sort of a weaselly answer, but my feeling is it's nice to use these nice materials, but if you are going to set up a production line, you look at the best material you can buy in production quantities and then that sets your target as to what your line efficiency would be.

RALPH: Basically, is it a Green cell design or something different?

ILES: It's shallow-diffused, probably textured, if you are going to do some external cooling of some sort. Probably textured with a multilayered coating and presence of contacts. And, I'll point out, without surface passivation, and without contact passivation I believe you cannot go over 17% anyway.

RALPH: To get to 19% or so are you still going to have to surface passivate?

ILES: At 19% you are going to have to do surface passivation to get the voltage up and if you want to agree there consistently, you have to keep the contacts out of it.

SCHRODER: In the quest for the high-efficiency cell, in your view, what would be the three most important problems that you face today, or perhaps the most unknowns today? Not 10 or 12, but the top three.

ILES: I think the most important thing would be to find a process sequence. Well, first of all, choose the material, you have to choose the material, because that fixes your design, and there are several competitive designs. The second is quite important -- that you pick a process sequence that can really take you up all the way and not sort of falter as you go. You don't need super-processing at each stage, but you need each stage to be done very well, and I think you choose a sequence maybe where these trade-offs are made. There are certain trade-offs, as there are in any semiconductor device, and it's how you fit into the trade-off that matters. Now in the past, some of those trade-offs have been internal technology that -- like a guy has only a shadow mask, so he says I can't get very good shading areas so I'll make up for it, I'll do something else that's very clever, and I'll stress that I've got some advantage, even though I don't have a good process. I think when you are getting up to 19% or 20% you have to have everything working very well -- the whole sequence has to work very well.

SIRTLL: Peter, you made a fairly strong point on the material, of course, and the worst thing that could happen after the meeting is a strong inflow of orders to get the super-material, or something that would come near to it. I think I should comment a little more on that. On the one hand, when you get some extraordinarily good material on the float-zone side, it has to be a byproduct of a much larger portion on a production scale. That's where the money has to come from. So in every case, such a kind

of material would always be very limited. Of course, it could be supported in terms of a project being made out of a long-range task to create, under any circumstances, such a super-material. But, on the other hand, if you remember, I made a strong point yesterday on the subject of gettering. I think the science of gettering still is in its infancy. My expectations, at least, go stronger in this direction -- that we would learn, over the years to come, a lot more about gettering and to handle material that can be produced under reasonable cost conditions and give it the final touch by the most appropriate gettering system. And that, of course, has to vary from one type of cell, or type of processing, to another.

ILES: I think that's a good point. It takes us away from the route of having to have clean rooms at every stage and building a whole extensive processing sequence. That's philosophically a nice approach. Do you think there's no chance of scaling-up for float-zone? There is obviously not a large enough market now, but supposing somebody said there was a quarter of a gigawatt market.

SIRTLE: I have my serious doubts with it, economically, that this would ever be able to work.

LOFERSKI: Peter, you made a rather strong point, and I think I agree with it, that the significance of what one has to do is to make it happen in the real world, on real-world materials. I think my understanding of how the process might go is that on the one hand you have to understand all the bits and pieces of how -- perhaps in the laboratory -- you would reach a 20% level, which might translate in the real world to an 18% level. In that regard, perhaps the Cz material in its finest form might be capable of that kind of quality. The point about understanding what is required to get to the very highest level you can is also important, and in that sense -- having determined that -- now you attempt to apply that with the things that are available. I believe that is the next step that should, and perhaps will, take place. The float-zone material -- you are putting all the load on the guy producing the material -- and the Czochralski, I think we are implying some sort of in-line gettering or updating or whatever. I think that's important. If you tell a manufacturing man "Here is what we want you to make -- oh, by the way, you are not going to get that material, you are going to have to somehow or other in that sequence put a gettering thing in there," that's not fair to him. I think you have to present him with the two options and see which he can produce. I think in a sense you are right, but I think the conception that was held at the time when the high-efficiency work that I am supporting was put in place was simply: let us, in terms of understanding the details, remove as many of the roadblocks as we can. Let's work on the best material available to see what comes out. If you know you have a number of defects in the materials that are going to be limiting features, no matter how well you do the job, and no matter how good your understanding, you will be hindered by that. Perhaps after you understand what's required you then work your way around this one point, and knowing you might get the answer is better than saying "We think we can get the answer. Let us try to find the way without knowing where the pitfalls might possibly be." We are a little sensitive, because we are like the guy who can jump 7'9"

but we can't tell anyone else how to jump 7'9". I'd hate to see a sprinter trying to jump 7'9".

ILES: When you are talking about a 20% cell, you cannot put all the burden on material; I think your earlier comment was well taken. So it's very important that we know how to make this 20% cell in the laboratory so that eventually one can optimize a cost or simplify later.

SWANSON: Peter, we have seen in selected Czochralski wafers, 10 to 20 ohm-centimeter resistivity range, as high a lifetime as we have seen in float-zone, and that was about four years ago. It was very sporadic, and averaged more like 20 microseconds to 50 microseconds. I think today, perhaps, with much more understanding on controlling oxygen concentration, that a serious effort to go back and try to learn how to get the lifetime up in Czochralski would be successful, in light of the better material today. What we found is that the gettering procedures that have been optimized around generation lifetime considerations are simply not appropriate, and generally do not work when you are concerned with recombination lifetime in the bulk of the material.

ILES: If you want to make fast-switching solar cells in good shape.